FULL TITLE
ASP Conference Series, Vol. **VOLUME**, © **YEAR OF PUBLICATION**
NAMES OF EDITORS

A new evolutionary scenario for the formation of massive black-hole binaries such as M33 X-7 and IC 10 X-1

S.E. de Mink[1], M. Cantiello[1], N. Langer[2,1], O.R. Pols[1] and S.-Ch Yoon[2]

[1] *Astronomical Institute Utrecht, Princetonplein 5, 3584 CC Utrecht, The Netherlands, S.E.deMink@uu.nl*

[2] *Argelander-Institut für Astronomie, Auf den Hügel 71, 53121 Bonn, Germany*

Abstract.

The formation of close massive black-hole binaries is a challenge for binary evolutionary models, especially the intriguing system M33 X-7 which harbours one of the most massive stellar-mass black holes (16 $M_\odot$) orbiting a 70 $M_\odot$ O-star every 3.5 days. In standard binary evolution theory an episode of mass transfer or common envelope is inevitable in a binary with such a small orbital period, which complicates the formation of a black hole with such a high mass.

To explain this system, we discuss a new binary evolution channel (De Mink et al. 2009), in which rotational mixing plays an important role. In very massive close binaries, tides force the rotation rate of the stars to be so high that rotationally induced mixing becomes very efficient. Helium produced in the center is mixed throughout the envelope. Instead of expanding during their main-sequence evolution (with the inevitable consequence of mass transfer), these stars stay compact, and avoid filling their Roche lobe. They gradually evolve into massive helium stars. This scenario naturally leads to the formation of very massive black holes in a very close orbit with a less evolved massive companion such as M33 X-7.

1 Introduction

The black holes in the X-ray binaries M33 X-7 and IC10 X-1 are two of the most massive stellar-mass black holes: $15.65 \pm 1.45 M_\odot$ (Orosz et al. 2007) and 23-34 $M_\odot$(Prestwich et al. 2007; Silverman & Filippenko 2008) respectively. Such high masses require that the progenitor star was very massive and experienced only a moderate mass-loss rate (e.g. Belczynski et al. 2009). However, both black holes orbit a massive companion star in an close orbit: 3.45 days in the case of M33 X-7 and 1.43 days in the case of IC10 X-1. These orbits are so tight that radius of the progenitor star must have been larger than the current separation between the stars. This implies that the progenitor experienced severe mass loss via Roche-lobe overflow. This is in contradiction with the very moderate mass loss rate required to achieve such a high mass for the black hole. Explaining both the high mass of the black hole and the tight orbit simultaneously is a major challenge for binary evolution models. Here, we discuss an alternative evolutionary scenario for very close massive binaries in which mass loss by Roche-lobe overflow is avoided.

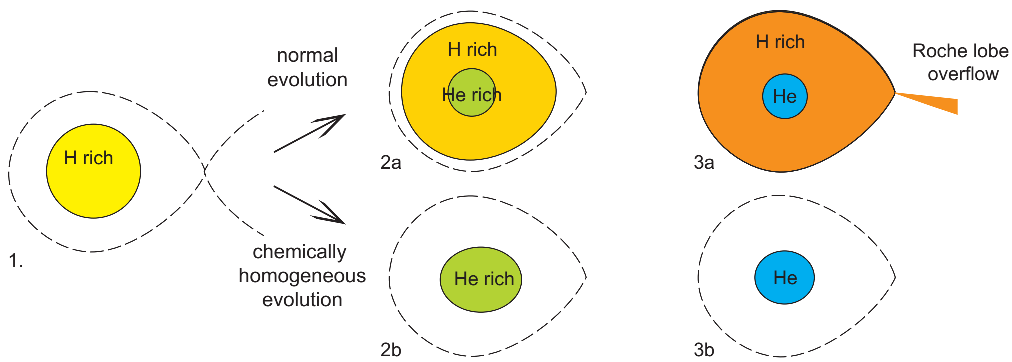

Figure 1. Cartoon representation of normal and chemically homogeneous evolution in a binary system, adapted from De Mink et al. (2008)

2 Rotational mixing in massive binaries

In models of rapidly rotating, massive stars, rotational mixing can efficiently transport centrally produced helium throughout the stellar envelope. Instead of expanding during core H-burning as non-rotating models do, they stay compact, become more luminous and move blue-wards in the Hertzsprung-Russell diagram (Maeder 1987). This type of evolution is often referred to as (quasi-)chemically homogeneous evolution and has been proposed for the formation of long gamma-ray burst progenitors (Yoon et al. 2006; Woosley & Heger 2006).

High rotation rates can be readily achieved in binary systems due to mass and angular momentum transfer (Cantiello et al. 2007) and also by tidal interaction in close binaries (Detmers et al. 2008). In De Mink et al. (2009) we demonstrated that even in detached, tidally-locked binaries, rotational mixing can lead to chemically homogeneous evolution. In these models it is the less massive star, in which the effects of rotational mixing are less pronounced, that fills its Roche lobe first, contrary to what classical binary evolution theory predicts. In single stars this type of evolution only occurs at low metallicity, because at solar metallicity mass and angular momentum loss in the form of a stellar wind spins down the stars and prevents initially rapidly rotating stars from following nearly chemically homogeneous evolutionary tracks (Yoon et al. 2006; Brott & et al. 2009). In a close binary tides can replenish the angular momentum, opening the possibility for chemically homogeneous evolution in the solar neighbourhood.

3 The formation of short-period black-hole binaries

The binary models presented by De Mink et al. (2009) all evolve into contact, due to expansion of the secondary star. However, Roche-lobe overflow may be avoided altogether in systems in which the secondary stays compact, either because it also evolves chemically homogeneously, which may occur if $M_1 \approx M_2$, or because it evolves on a much longer timescale than the primary, when $M_2 \ll M_1$. Whereas standard binary evolution theory predicts that the smaller

the orbital period, the earlier mass transfer sets in, they find that binaries with the smallest orbital periods may avoid the onset of mass transfer altogether, see Fig. 1. This evolutionary scenario does not fit in the traditional classification of interacting binaries (Case *A*, *B* and *C*), which is based on the evolutionary stage of the primary component at the onset of mass transfer (Kippenhahn & Weigert 1967; Lauterborn 1970). In the remainder of this paper we will refer to this new case of binary evolution, in which mass transfer is delayed or avoided altogether as a result of very efficient internal mixing, as Case *M*.

The massive and tight systems in which Case *M* can occur are rare (De Mink et al. 2008). Additional mixing processes induced by the presence of the companion star, which may be important in such systems, will widen the parameter space in which Case *M* can occur: it would lower the minimum mass for the primary star and increase the orbital period below which this type of evolution occurs. The massive LMC binary [L72] LH 54-425, with an orbital period of 2.25 d (Williams et al. 2008) may be a candidate for this type of evolution. Another interesting case is the galactic binary WR20a, which consists of two core hydrogen burning stars of $82.7 \pm 5.5\mathrm{M}_{\odot}$and $81.9 \pm 5.5\mathrm{M}_{\odot}$ in an orbit of 3.69 d. Both stars are so compact that they are detached. The surface abundances show evidence for rotational mixing: a nitrogen abundance of six times solar, while carbon is depleted (Bonanos et al. 2004; Rauw et al. 2005).

If Roche-lobe overflow is avoided throughout the core hydrogen-burning phase of the primary star, both stars will stay compact while the primary gradually becomes a helium star and can be observed as a Wolf-Rayet star. Initially the Wolf-Rayet star will be more massive than its main sequence companion, but mass loss due to the strong stellar wind may reverse the mass ratio, especially in systems which started with nearly equal masses. Examples of observed short-period Wolf-Rayet binaries with a main-sequence companion are CQ Cep, CX Cep, HD 193576 and the very massive system HD 311884 (van der Hucht 2001). Such systems are thought to be the result of very non-conservative mass transfer or a common envelope phase (e.g. Petrovic et al. 2005). Case M constitutes an alternative formation scenario which does not involve mass transfer.

Case *M* is particularly interesting for the formation of massive black-hole binaries, such as M33 X-7 and IC 10 X-1. The explanation for the formation of these systems with standard binary evolutionary models or synthetic models (e.g. Abubekerov et al. 2009) involve a common-envelope phase that sets in after the end of core helium burning, as the progenitor of the black hole must have had a radius much larger than the current orbital separation. This scenario is problematic as it requires the black-hole progenitor to lose roughly ten times less mass before the onset of Roche-lobe overflow than what is currently predicted by stellar evolution models (Orosz et al. 2007). An additional problem is that the most likely outcome of the common envelope phase would be a merger, as the envelopes of massive stars are tightly bound (Podsiadlowski et al. 2003). In the Case *M* scenario the black hole progenitor stays compact and avoids Roche-lobe overflow, at least until the end of core helium burning.

4 Conclusion

We propose an alternative formation scenario for close massive black hole binaries, such as M33 X-7 and IC10 X-1. In this scenario the system starts initially as a very close binary in which tides force the stars to rotate rapidly. This induces mixing processes in the progenitor of the black hole, which as a result stays compact within its Roche lobe. Whereas the short orbital period is a major challenge for classical binary evolution scenarios, in this scenario it constitutes an essential ingredient: it results in tidal-locking of the stellar rotation to the fast revolution of the orbit. The high mass of the black hole is naturally explained by this scenario: efficient mixing leads to the formation of very massive helium stars and consequently massive black holes.

Opportunities to test the validity of this scenario for M33 X-7 may come from the properties of the companion star (Valsecchi et al. 2009) and the high Kerr parameter of the black-hole (Liu et al. 2008), which according to Méndez (2009) can only be explained with hypercritical accretion onto the black-hole. Further modelling is needed to validate this statement in the light of this new evolutionary scenario.

References

Abubekerov M. K., Antokhina E. A., Bogomazov A. I., Cherepashchuk A. M., 2009, Astronomy Reports 53, 232

Belczynski K., Bulik T., Fryer C. L., Ruiter A., Vink J. S., Hurley J. R., 2009, ArXiv/0904.2784

Bonanos A. Z., Stanek K. Z., Udalski A., Wyrzykowski L., Żebruń K., Kubiak M., Szymański M. K., Szewczyk O., Pietrzyński G., Soszyński I., 2004, ApJ 611, L33

Brott I., et al., 2009, in prep.

Cantiello M., Yoon S.-C., Langer N., Livio M., 2007, A&A 465, L29

De Mink S. E., Cantiello M., Langer N., Pols O. R., Brott I., Yoon S.-C., 2009, A&A 497, 243

De Mink S. E., Cantiello M., Langer N., Yoon S.-C., Brott I., Glebbeek E., Verkoulen M., Pols O. R., 2008, in L. Deng, K. L. Chan (eds.), IAU Symposium, Vol. 252 of *IAU Symposium*, 365

Detmers R. G., Langer N., Podsiadlowski P., Izzard R. G., 2008, A&A 484, 831

Kippenhahn R., Weigert A., 1967, Zeitschrift fur Astrophysik 65, 251

Lauterborn D., 1970, A&A 7, 150

Liu J., McClintock J. E., Narayan R., Davis S. W., Orosz J. A., 2008, ApJ 679, L37

Maeder A., 1987, A&A 178, 159

Méndez E. M., 2009, in C. Meegan, C. Kouveliotou, N. Gehrels (eds.), American Institute of Physics Conference Series, Vol. 1133 of *American Institute of Physics Conference Series*, 109

Orosz J. A., McClintock J. E., Narayan R., Bailyn C. D., Hartman J. D., Macri L., Liu J., Pietsch W., Remillard R. A., Shporer A., Mazeh T., 2007, Nat 449, 872

Petrovic J., Langer N., van der Hucht K. A., 2005, A&A 435, 1013

Podsiadlowski P., Rappaport S., Han Z., 2003, MNRAS 341, 385

Prestwich A. H., Kilgard R., Crowther P. A., Carpano S., Pollock A. M. T., Zezas A., Saar S. H., Roberts T. P., Ward M. J., 2007, ApJ 669, L21

Rauw G., Crowther P. A., De Becker M., Gosset E., Nazé Y., Sana H., van der Hucht K. A., Vreux J.-M., Williams P. M., 2005, A&A 432, 985

Silverman J. M., Filippenko A. V., 2008, ApJ 678, L17

Valsecchi F., Willems B., Fragos T., Kalogera V., 2009, ArXiv/0902.3700

van der Hucht K. A., 2001, New Astronomy Review 45, 135
Williams S. J., Gies D. R., Henry T. J., et al., 2008, ApJ 682, 492
Woosley S. E., Heger A., 2006, ApJ 637, 914
Yoon S.-C., Langer N., Norman C., 2006, A&A 460, 199